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CERTAIN PHASES OF GLACIAL EROSION

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Oscillation, more or less rhythmic, seems to be a phenomenon of the intellectual, as well as of the physical world. The doctrine of glacial erosion has its ups and downs in quite typical undulatory fashion. It seems that even individuals at times ride on the crest of the wave of advocacy and at other times sink into the hollows of doubt. These moods are apt so to distribute themselves that while some workers are on the crest others are in the trough. The crest-riders have recently been much the most in view, but just now voices from the hollows of doubt are heard. The president of the British Association for the Advancement of Science, speaking from official vantage ground, voices a cautious skepticism as to the glacial parentage of certain kinds of configurations that are held by others to be the erosive offspring of glaciers.[1] Professor Garwood goes beyond the measured skepticism of Dr. Bonney and gives a critical analysis of his grounds of doubt and laudably matches his destructive criticism with constructive interpretations. In these interpretations, he marshals topographic phenomena in support of the view that *protection*[2] is the characteristic effect of glaciers rather than erosion.

[1] T. G. Bonney, Presidential Address before B.A.A.S. (Sheffield, 1910), *Science*, XXXII (1910), 321–36, 353–63.

[2] E. J. Garwood, "Features of Alpine Scenery Due to Glacial Protection," *Geog. Jour.* (September, 1910), pp. 310–39.

So, too, among those who believe in the efficiency of glacial erosion, there has long been some doubt as to the truth, or at least as to the adequacy, of some of the processes to which the erosion has been attributed.

It seems worth while, therefore, to add to the growing mass of matter some notes suggested by phenomena recently seen by us, without presuming that much is new either in the observations or in the suggestions.

I. THE CRITICAL STAGE FROM WHICH CERTAIN EROSION TYPES START

It has seemed to us advantageous to study the initial stages of erosion to see, if possible, precisely what action gives the start to the type of erosion which thereafter controls the configuration, for it is the initial turn that most delicately measures the balance between the opposing tendencies.

The contours that spring from ordinary wear and weathering are well known and may be restored from remnants when the greater part has been lost. Even when there has been no change in the agent and only a slight change in its mode of action, the old configuration can be distinguished from the new; as, for familiar example, the remnants of a peneplain are commonly made out with confidence after most of the plain has been cut away by the rejuvenation of the very drainage system that formed it. Much more clearly can remnants of contours be rebuilt into their originals when some *new* agency intervenes, especially a new agency whose habit of sculpture is distinctively at variance with that of the previous agency.

As surface configurations are traced from regions dominated wholly by ordinary wear and weathering into regions that have been affected by local glaciation, it is usual to find the lower slopes of the unglaciated region and, in the main, the brows and tops of its hills and higher elevations, up to a certain limit, marked by contours of the familiar wear-and-weather type whose interpretation is clear and whose restoration, when mutilated, may be made with great confidence. As such contours are traced into higher latitudes or higher altitudes where local glaciation has entered

sparsely as a modifying factor, it is usual to find the flowing contours of the wear-and-weather type replaced in certain spots by a type that may be said to be unconformable to the prevalent one, a type in which concavity replaces convexity, a type in which the surface has been broadly scooped out locally rather than rounded off generally or narrowly incised. The broad scoop-like mode of excavation, as distinguished from the gully-form mode of narrow incision, is held to be distinctive in that it implies an agency that deployed its effects laterally rather than one which concentrated its action on axial lines. This, it is to be noted by way of precaution, is a distinction that applies chiefly to the initial stage of the two modes of erosion. They remain distinguished throughout but are not so declaredly diverse in later stages.

The lodgment of snow, which is the primary factor in glacial work and determines its initial deployment, is controlled by the wind to an exceptional degree, and wind action is chiefly horizontal in its effects and is thus distinguished from rainfall and run-off, whose dominant actions are vertical. While the very first phases of this difference of action are not very important in themselves, they are believed to be significant as the initial factors in the localization as well as the deployment of the two classes of erosion.

The relative locations of greatest rain-work and greatest snow-work respectively.—Precipitation is intimately dependent on the ascent of air so well laden with moisture that it reaches saturation by reason of the expansion and cooling caused by the ascent. It is for this reason that the ascent of moist air caused by rising over the windward face of any marked relief of the topography determines precipitation on or near that face. As is well known the windward sides of mountain chains thus receive more precipitation than the leeward sides, as a rule. This holds true of snow-precipitation as well as rain, though the snowfall is less prompt and less well localized. Where mountain ranges are broad and complex the snow caught on the windward side is usually greater than that which lodges on the leeward side, and the glaciers on the windward sides of mountain ranges are usually larger than those on the leeward sides. But such *general* community of distribution does not hold in detail, for the wind comes in as a

local differentiating agency. Acting on rain, wind increases the amount per unit area that strikes the surface of an eminence on its windward side; it also somewhat increases the force of the impact on that side. On the other hand, wind tends to drive falling and fallen snow around the wind-swept side of the eminence into its lee and to heap it up in the eddies there, and on the areas protected from the wind. Thus the snowfall that, in the absence

FIG. 1.—Snow lodgment on the side of the summit ridge of Mt. Victoria, Canadian Rockies. This ridge forms the continental divide. The snow has lodged on the Eastern or Albertan side in the lee of the crest. Photo. by R. T. C.

of wind, would come to rest on the windward and lateral slopes of an eminence and later must drain away on these slopes is, under the action of wind, concentrated notably in patches in the lee. Considered therefore in detail, rain action is somewhat intensified on the windward side of prominences, while snow lodgment, leading on toward glacial action, is more markedly concentrated on their leeward slopes.

The field use of this distinctive localization of rain-work and of snow-work respectively is qualified by the fact that, while the

prevalent air movement of a region may be nearly constant in *general*, the cyclonic movements that are the immediate agents that bring on precipitation introduce variation in the *particular* direction from which the wind blows at the critical time when the storm is on and the distinctive work in question is done. In the mid-latitudes of the northern hemispheres, the general air movement is toward the east but at the times of storms the wind not uncommonly comes from the eastward. However, the general law that snow lodgment is most abundant on the prevailingly leeward sides of prominences seems to hold good. This is greatly aided by the shifting that takes place in the intervals between storms.

The fact that the eddies formed in the lee of crests, domes, and knobs are the common spots of lodgment carries as a corollary the observation that the forms of the snowfields are usually broad, or ovoid. The windward edge is usually arched, and is often thickened near its upper border. Not unfrequently the thickened snow mass is wider transversely than in the line of slope. Often, too, it must be noted, the lodgment is concentrated in ravines and valleys that were shaped previously by drainage erosion, and in such cases the localization is less distinctive.

The case best suited to a discriminative study is a broad or transversely elongate lodgment of snow in the lee of a well-rounded eminence from which the normal run-off is divergent. So long as such a snow mass lies passively where it lodged, there can be little doubt that it is protective rather than erosive, when compared with normal surface action. So long, too, as the later action is confined to a slow annual melting of the snow and a quiet run-off of the resulting water, the snow and water combined perhaps do less erosive work, on the whole, than would be done by the more forceful impact and the more prompt run-off of the equivalent rain, though qualifying conditions must be recognized on both sides.

The case of snow vs. rain, under these conditions, is not more than debatable at most and the modes of erosion in the two cases are essentially identical.

But when the snow accumulates perennially so as to move as snow-ice in glacier fashion, the modes of erosion become diverse,

and *the configuration of the eroded surface* is the test of the dominance of the one or the other type. It is obvious that the least eroded part of the eminence must come to stand forth and the

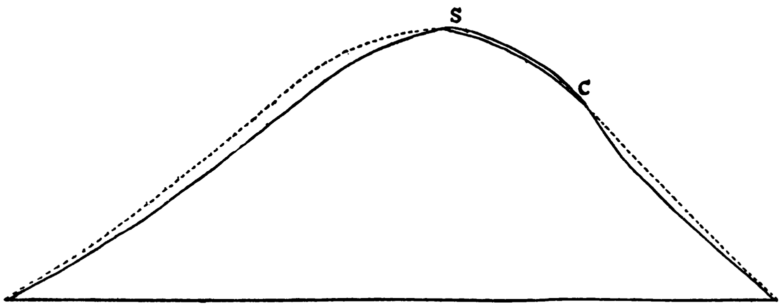

FIG. 2.—Diagram to illustrate the effect of erosion upon a hill, on the assumption that the capping of ice, SC, is protective. The dotted line represents the original outline of the hill; the solid line, the contour resulting from erosion.

most eroded part must retire toward the center. If the snow-covered flank or brow is indeed a protected area, it must gradually come to stand forth from the retiring wear-and-weather contours

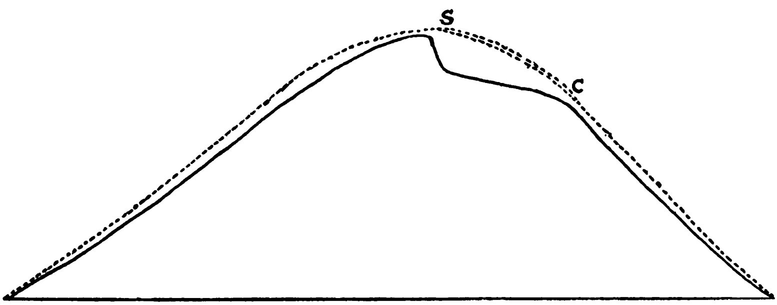

FIG. 3.—The same hill as in Fig. 2, eroded according to the hypothesis that ice is a superior eroding agent. SC represents the original snow bank which comes to occupy a basin as erosion goes on.

adjacent, as a rather definite embossment, as illustrated in Fig. 2. As time goes on, the summit of the hill should migrate toward this protected area and it should tend to become the summit, while the snow-cap in turn migrates into its lee. A marked asymmetry should gradually develop.

On the other hand, if the snow mass, accumulating from year

to year, comes to take on motion as a glacial body, the erosion to which its motion gives rise must take a form coincident with the moving part of the snow-ice mass. The erosion is assumed to be due to the adhesion of the snow-ice mass to the ground on which it rests—to the soil and loose rock at the start, to the progressively loosened and ground rock below later. A broad patch of soil and loose rock coincident in form with the moving part of the snow mass is first dragged away and the configuration of the scar is distinctive of the action. If erosion beneath the moving glacier mass continues the excavation will in time come to have the form shown in Fig. 3. Such excavations are to be looked upon as embryo cirques. They are found on the lee crests, brows, and slopes of round-topped mountains known to have been subjected to local glaciation. Less typical initial cirques are formed in ravines where snow lodgment gives rise to glaciers.

If absolute certainty that there has never been any previous glacial action in a given region is regarded as a prerequisite to an irreproachable illustration of this class of actions, such a case is difficult to demonstrate because the configurations left by the older glaciations have often been so largely lost in the subsequent sculpturing of the common wear-and-weather type that the absence of previous glacial work is hard to prove in regions likely to have been glaciated recently, but this is only a question between the work of different glacial stages, not between glacial and aqueous methods. But though a region has been subjected to previous *general* glaciation, even rather recently, geologically speaking, the typical effects of local glaciation on rounded contours are discernible much as in wholly unglaciated regions, for the contours shaped by the *general* ice movement conform to the dominant horizontality or the low inclination of such general ice movements, while the lines of local ice movement are decisively downward in conformity to the *local* slope.

These considerations are here put in the theoretical form, but they suggested themselves almost as inductions during a summer trip along the coast of Norway in 1909. They arose naturally from the abundant and instructive phenomena of that region, where former glacial action merges into present action. The configurations

wrought by the older general glaciations do not seriously mask the distinctive work of the local glaciation that has followed and is, in some part, in action still. Broad excavations of the initial cirque type are common on the brows and slopes of the rounded mountains and on the islands that fringe this coast and on the mainland itself. They seemed to us clearly to be more common on the eastward sides of the islands than on the westward. The initial types are chiefly the products of modern action; indeed in

FIG. 4.—Basins hollowed in a hillside by tiny glaciers. From the coast of Norway. Photo. by R. T. C.

many cases the basins are still occupied by the snow-ice mass to which their shaping is due. The whole series taken together show various stages of the work of snow accumulation and earth excavation. Small, relatively wide basins, scooped broadly from hillsides, are variously occupied or empty according to altitude, latitude, or other condition favoring snow accretion or snow wastage. Their dimensions range downward to hollows not unlike pits on the brows of drift hills and upward to mountain cirques of typical form and magnitude. They also range from mere cirque heads to cirque heads with short glacial appendages and thence on to longer and longer glacial tails until the peculiarities of the

head-work in the cirques are lost in the more familiar body-work and tail-work of the more accessible parts. Various stages and transitions are shown in the accompanying photographs.

Fig. 4 shows five well-developed basins escalloped in a hillside. The two hollows on the left are round and wide and terminate below in well-defined platforms or steps at nearly the same level.

FIG. 5.—A concave scallop on the brow of a projecting embossment. Apparently this is the work of sapping by the ice at the base of the cliff. Note the rounded convex glacier-polished outlines of the rest of the embossment. In the background is the Lyskamm, central Pennine Alps. Photo. by R. T. C.

They are approximately as wide as they are long, showing that the ice which accumulated there has eaten its way in a distinctly broad fashion into the rock slope on which it lay. The vertical distance which any given part of the ice has moved its rock is small relative to the total amount of transportation accomplished. The work has been done very locally compared with the longitudinal movement of typical water action. The next two basins continue down the slopes to points much nearer to the sea. There has been

more advance movement of the ice here. The basin on the right has become a glacial valley in an embryonic stage and the work of water erosion seems to form a larger factor.

Sculpturing of similar sort is illustrated by Fig. 5, from the Swiss Alps. The brow of a long spur descending from the Zwillinge has been scooped and hollowed in concave fashion by the sapping action of glacier ice. Occurring in the midst of a still

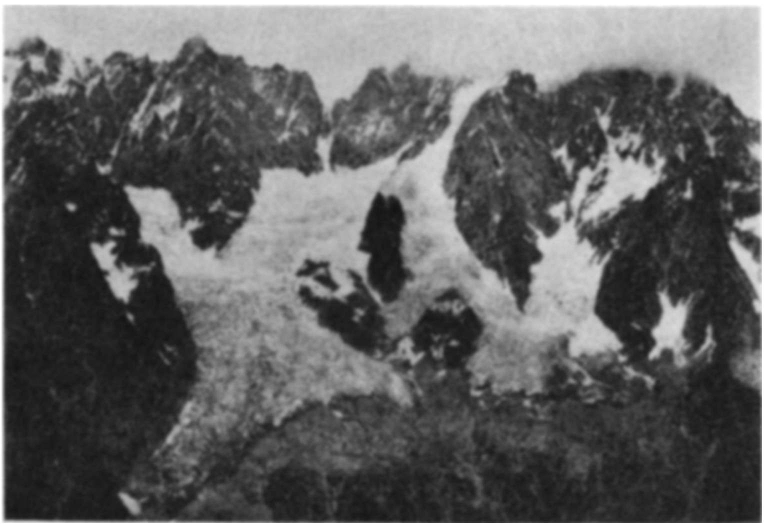

FIG. 6.—The Glacier des Grandes Jorasses on the Italian side of the chain of Mont Blanc. The ice has sunk its bed into the rocky mountain wall and worked backward as implied by the distinct bench upon which it rests. Photo. by R. T. C.

strongly glaciated area, this case is interesting for the reason that such sculpturing has been at work here for a comparatively short time only. The rounded rock contours below and to the right of the hollow excavation have at no distant date been scraped and polished by the larger glaciers descending from the peaks above. The ordinary abrasive action of a moving body of ice is here illustrated. But the much smaller mass of snow and ice at the base of the cliff in the hollow appears to have operated in the very different and more potent manner of basal sapping at the schrund line.

Fig. 6, from the chain of Mont Blanc, represents the Glacier des Grandes Jorasses on the Italian side of the rugged mountain mass of the same name. Other similar glaciers to the left and right have etched their basins into the upper slopes of this great mountain rampart. These glacier-filled basins are deeply sunken and are as broad or broader near the base of their cirque walls than they are farther down toward the ends of the present ice tongues. At their heads they are terminated by precipitous rock walls. Extremely precipitous cliffs come down to the Glacier de Rochfort from the Aiguille du Géant and the col between it and the Aiguilles Marbrées. From these rock walls behind the ice there is a very decided change in slope to the gentle incline of the glacier floor below. In just the same way there is a very abrupt change of slope from the precipitous rocks of the Grandes Jorasses and Mont Mallet to the very moderately inclined surface of the Glacier des Grandes Jorasses at the foot of these steep cliffs. It is at the point where these cliffs join the less inclined basin floor beneath the glacier that the greatest cutting has occurred. Such a profile of cliff and floor coming together at a sharp angle is quite unlike any gully erosion developed by ordinary running water in mountains of massive crystalline rocks. The greatest cutting has been beneath the glacier in the neighborhood of the bergschrund and directed backward into the mountain.

II. CERTAIN SIGNIFICANT POSITIONS OF CIRQUES

In our sketch of the initiation of cirques, we gave preference to cases located on leeward aspects of eminences favorable for snow lodgment but unfavorable for the concentration of running water. We noted that if the lee brow were *protected* by its snow covering, the crest should slowly shift toward the protected spot and the protecting snow-cap should shift in turn to its lee and thus combine to shape forth an asymmetrical mountain horn. On the other hand, if the snow mass becomes a superior *erosive* agent when it begins motion, and digs out a broad basin which in turn adds to the catchment of snow, and if at the same time the embryonic glacier stopes headward, it, in its way, *moves toward a summit position.* It is clear that rainfall does not concentrate toward

the summit of a rounded eminence in this way. Its trenches do advance headward, but they take the form of ravines, gulches, and gullies eating sharply, not broadly, backward. The positions of cirques that are fully developed may be studied for evidence confirmatory of these deductions. In such study perhaps the most striking illustration of summit-ward creep is found in the *crater cirques*, a form that has attracted the attention of observant travelers but has not played as large a part in glacial literature as

FIG. 7.—The Rendalstind on the west side of the Lyngenfjord, Norway. The summit has become crater-shaped by ice sculpturing. Photo. by R. T. C.

perhaps it should. Mountains with crater-like summits are quite common along the Norwegian coast above the Arctic Circle, and they are likewise frequent enough in the Lofoten Islands to give characteristic profiles to the views obtained there from passing steamers.

The Rendalstind, on the west side of the Lyngenfjord (Fig. 7), is an illustration of the type in a not very advanced stage of development. Glacier action in the summit basin is today actively in progress. Other mountains of the region reveal much more pronounced sculpturing of this sort where the action has either been more prolonged or more intense. Such a case is illustrated by

Fig. 8. This crater mountain, which happens to be crossed by the 70th parallel, comprises the north end of Kaagö Island. Originally it appears clearly to have been a more or less rounded dome or knob. A cirque starting with snow lodgment high up on the northeast slope of this eminence appears to have worked back

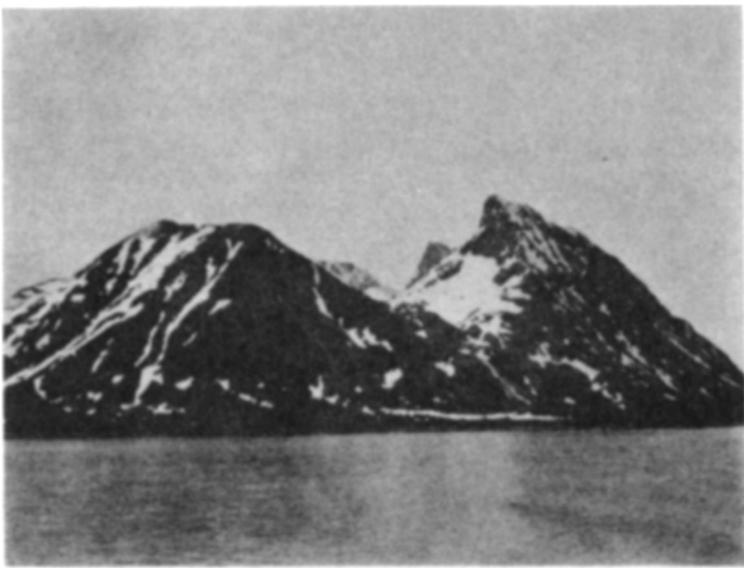

Fig. 8.—A crater-like mountain top in a more advanced stage of erosion. The outer slopes of the conical mass show the familiar abrasive action of past general glaciation together with the lines of ordinary meteoric erosion. The steep walls of crater-like cirque are due to sapping by localized glaciers of late date. Kaagö Island, coast of Norway. Photo. by R. T. C.

toward the summit by a stoping process until the cirque pit has come to occupy a sub-summit position. The mountain top has been hollowed out and now only a shell remains in place of the former flat-topped mass. It is like a volcanic crater broken down on one side. The inner walls are steep and cirque-like and the crater portion is filled with deep snow. Water erosion is not adapted to this sort of sculpturing. The central basin with circular cirque cliffs gives every appearance of having resulted from

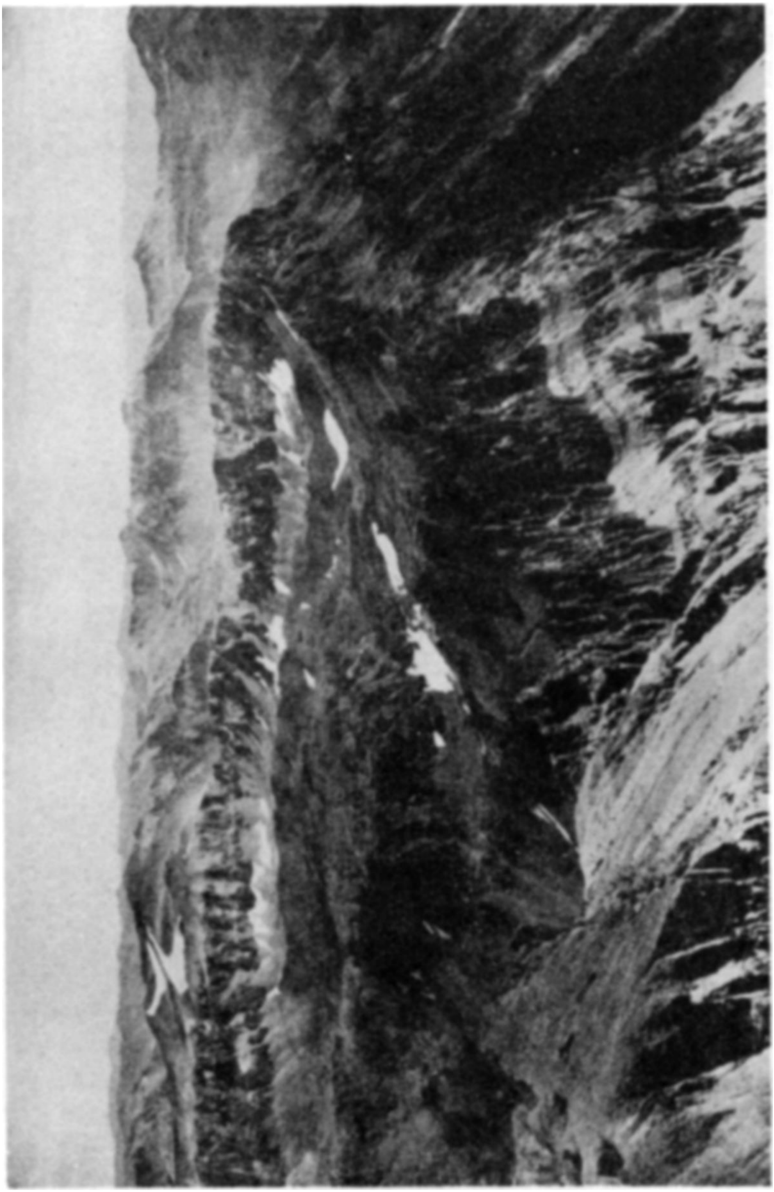

FIG. 9.—A very capacious summit cirque in the San Juan Mountains of Colorado. Seen looking southeast from the culminating point of St. Sophia Ridge, Telluride quadrangle. The points of note are the breadth of the cirque basin and the narrowness of the serrate rim. The abrupt step in the middle of the basin while partly the result of stoping beneath the body of the glacier was also probably in part determined by differences in the resistance of the rock formation. Photo. by R. T. C.

continued sapping and quarrying by glaciers eating their way backward much as they have in the Alpine cases cited.

Fig. 9, from the San Juan Mountains of southwestern Colorado, is a striking example of a much more capacious summit cirque. The basin here is very broad, with a nearly level floor, while the cirque rim has been undercut till only a narrow horseshoe-shaped serrate ridge remains. Its jagged crest varies in altitude from 13,000 to 13,200 feet, while the mean elevation of the broad floor is about 12,800 feet. The breadth of the basin and the steepness and thinness of the amphitheater walls that skirt it show that this type of action has here gone about as far as it well could as a single stoping operation. The whole constitutes a signal case at its very climax.

In the light of these illustrations, particularly Figs. 8 and 9, there seems no ground to doubt that the erosion suffered by the non-glaciated parts in such situations at least falls greatly behind that suffered by the parts covered by ice.

III. THE DISTINCTIVE WORKING FACTOR

The decided superiority of moving ice over moving water as an erosive agent lies chiefly, we think, in the rigid hold of the ice on matter set in its base or sides. This is sharply contrasted with the adhesion of water which is so feeble as to scarcely warrant the term "hold" at all. Water action finds some compensation, indeed, in the higher velocity it usually gives to the matter it carries, but near the point of origin of action—and this is the location chiefly under discussion here—the water is so distributed as not to be able to acquire much efficiency from concentration. The ice mass, on the contrary, is rigidly unified; its velocity is indeed low, but its mass and fixed coherence are high. It is in respect to this coherence that exaggerated views of the viscousness of ice are perhaps most misleading. Rigidity of grasp and mechanical firmness of action are specifically implied in the groovings, gougings, and crushings that distinguish the action of glaciers. Effectiveness of corrasive action is further implied in the chemical and physical nature of the rock-flour and fragments which these groovings, grindings, and crushings contribute to the glacial till

and to the wash-products immediately derived from it through glacio-fluvial assortment.[1] The graving of a glacier's bed by rock fragments set in its base or sides may be cited as specific evidence of an essentially rigid hold on the graving tools, and of an internally rigid, rather than fluent, motion of the mass holding the tools. The glacial grindings that are borne out with the subglacial waters and give milkiness to glacial streams seem to us irrefutable evidence of effective rasping and grooving of the rigid type, not of simple viscous overcreep. The very marked contrast between the turbid waters that flow from beneath glaciers and the relatively clear waters that flow down adjacent unglaciated valleys is very impressive and spectacular evidence of the superior erosive powers of glaciers.

Closely allied to this lesson from grindings in transit is a less obtrusive one drawn from the contrast in the points where coarser matter which only strong transporting agents can handle is concentrated respectively in glaciated and in non-glaciated valleys in regions of the same general type. The upper parts of non-glaciated mountain valleys in cold regions are usually burdened with heavy talus and large loose masses which the drainage is unable to carry away, while the glaciated parts of similar valleys are usually well scoured out and the moutonnéed sides and bottoms of U-shaped troughs take the place of the craggy outliers of V-shaped trenches in unglaciated valleys. But in the lower portions of the glaciated valleys below the reach of recent glacial action, *aggradation* very generally prevails, while in similar non-glaciated valleys *degradation* generally prevails, if not absolutely, at least relatively. Students of Alpine regions will recall multitudes of illustrations. A similar lesson is even more impressively enforced on the borders of the late Pleistocene glacial areas. In strong contrast to the state of the valleys of the adjacent driftless regions, the great glacio-fluvial valley trains with their thick heads next to the ice border, as well as the frontal aprons, show very conclusively the overladen condition of the glacial waters and their marked incompetency to fully carry away their burdens.

[1] "Hillocks of Angular Gravel and Disturbed Stratification," *Am. Jour. Sci.*, XXVII (May, 1884), 378–90.

Now the regional precipitation is much the same for like areas and like situations in the glaciated and in the non-glaciated valleys. Such differences as there may be appear to favor a greater run-off in the glaciated than in the non-glaciated basins, for the former are likely to be cooler and hence better condensers and the concentration of snow by wind action is there more effective. If so, the advantage in absolute carrying power lies with the waters of the glaciated valleys. If therefore the passing of a part of the precipitation through the glacial form and the moving of this part, so far as it moves as ice, is *protective*, the débris should tend to remain in the upper glaciated sections thus protected; while the waters of the valley below the glacier having some excess in volume and having less burden to carry should tend to degrade the lower reaches of the valley more effectively than if the glacier were absent. That the facts are precisely the opposite seems good additional evidence that the glacial form of water compared with the aqueous form increases notably the corrasion and the transporting power. And so it seems to us that the fringing outwash aprons and the thick-headed valley trains of the Pleistocene join with the aggraded states of the lower stretches of present glacial valleys and with their turbid glacial streams, their moutonnéed walls, and their glacial scorings to testify to the superior erosive efficiency of glaciers.

Traced back analytically to the properties that gave rise to them, these corrasive products point to a glacier's power to take firm hold on rock fragments imbedded in its base and sides and move them on while it uses them as graving tools. A special feature that is of interest here is the ice's habit of freezing to fragments in contact with it, especially when moisture is present. Ice also strengthens its adhesions by a tendency to freeze and thus to attach additional ice at points where tension is developed. This amounts to an inherent tendency to strengthen its hold when threatened with severance.

IV. THE EVOLUTION OF THE CIRQUE

In a young glacier-head just coming into action as the result of the growth of its stresses as a snow mass, it is inevitable that

at some point near the upper edge of the snow mass there should come to be a line of strain between the thicker part below that is forced to move and the thinner part above that lacks sufficient stress to take on motion. A low temperature is essential to the preservation of the elements that enter into the process. Through this low temperature the snow-ice mass has become adherent to the soil beneath it and more or less interlocked with the loose rock that may be at or near the surface. The motion of the snow-ice mass involves the motion of some part of this underlying material. Under the snow-protected stationary part the loose earth-surface remains behind. The line of division between the stationary protective snow and the moving abrasive snow-ice mass thus demarks a scar and this scar, if we interpret aright, is the embryo of the future cirque. As the process goes on and the excavation becomes deeper and by this deepening comes itself to aid in the catchment process, the line of transition from the ineffectively thin snow above to the effective deep snow below becomes more sharply defined. Thus the delimitation of the growing glacier-head and its product, the growing cirque, not only becomes more pronounced but the line of parting between the active and the inert becomes fixed by the process itself; and so the declared cirque becomes established and its bergschrund localized. With further progress the action graduates into the still more declared forms of the cirque-generating process.

In the exposition of Willard D. Johnson[1] as also in that of G. K. Gilbert,[2] both of which we accept in the main, the bergschrund is made the dominant agency in the cirque formation. The view just outlined carries the cirque-forming action back of even the cirque itself and, potentially at least, back of any bergschrund or any possible influence arising from the bergschrund. It makes the bergschrund and the cirque-development sequent on conditions and agencies that at an earlier stage controlled the snow-ice accumu-

[1] Willard D. Johnson, "The Profile of Maturity in Alpine Glacial Erosion," *Jour. of Geol.*, XII (1904), 569–78. Earlier papers are "An Unrecognized Process in Glacial Erosion," *Science* (1899), p. 106; "The Work of Glaciers in High Mountains," *ibid.*, 112–13.

[2] G. K. Gilbert, "Systematic Asymmetry of Crest Lines in the High Sierra of California," *Jour. of Geol.*, XII, 579–88.

lation and brought on motion in the thicker part of the mass while it left the thinner part stationary and protective. The bergschrund and the cirque cliff are themselves made sequences of a mobility and erosive competency more primitive than themselves. This in turn is contrasted with adjacent inertness and erosive inefficiency.

All this, however, seems to us wholly compatible with a cordial acceptance of the bergschrund and the cirque wall as auxiliary sequential agencies which strikingly abet the more primitive actions that brought them into being. Much as the bergschrund may aid the backward sapping of the cirque wall, we think that the more fundamental agencies are to be regarded as controlling the process throughout its history.

As already implied, a marked peculiarity of ice, shared in equal degree by no other familiar body, is its tendency to grow under tension and to form adhesions by such growth at the points where tension has been developed. When forced to part, ice parts suddenly by abrupt fracture attended by the elastic recoil of the separated faces. In this its action is in marked contrast to the separation of viscid bodies, which part by a gradual weakening and stretching under continued strain. Within the bergschrund, as also elsewhere and in general, the predisposition of the ice, when at the critical temperature of congelation and below, is to freeze to whatever falls in from the surface or is loosened from the walls. This tendency to form adhesions is no doubt especially active at the base of the schrund and at the foot of the cirque wall, where the convergence of the walls wedges all such matter together and where the conditions of temperature and moisture are likely to be favorable to glacial attachments in the active season. Whatever snow falls in, slides in, or is blown into the gaping mouth of the schrund, and whatever rock is detached from the cirque wall by the freezing of such waters as may come down the bergschrund are subject to such attachment to the head of the glacier and to removal by it as it moves, as Johnson has indicated. In addition to this, such waters as enter the mountain at any point above the cirque and traverse internal joints and later come out to the face of the cirque wall lower down are subject to freezing as they come near the

exposed portions of the face, and by expansion in the joints are likely to rive the wall rock and to detach fragments from it. It seems probable from the nature of the case that the exit of such internal drainage takes place more largely at or near the foot of the cirque wall than at higher levels. Such a localization of the action is specially fitted to promote basal sapping. If the sapping at the base of the cirque wall be thus made in some notable part dependent on the seepage of water from the mountain mass at or near the base of the wall, it will not perhaps seem strange that the sapping should proceed somewhat downward as well as backward, following in reverse the direction that the waters of seeps and springs usually take in issuing, and thus give rise to the important fact observed by Johnson that the floor of the cirque frequently inclines somewhat toward the cirque wall.[1]

In this view, the sapping is not made in any radical way dependent on diurnal changes of temperatuie due to the openness of the schrund above; rather it presumes that the base of the schrund will often be filled with snow, ice, or rock fragments fallen from above and that it will not be freely exposed to the briefer class of changes of temperature that affect the outer air. It does presume, however, that the mean temperature at the base of the schrund, and at the base of this part of the glacier generally, favors freezing whenever tension aids, and that it is favorable to glacial growth rather than glacial wastage, as this is the general fact in this part of a glacier. The periodicities of seasonal temperature and the variations attending the cyclonic movements of the atmosphere extending over some days seem to us more probably effective in the sapping at the base of the cirque wall than daily changes.

V. GLACIAL STEPS

Conditions somewhat similar to those of the cirque, save in the matter of the beginnings of motion, are often found at other points along the length of the glacier below the cirque. They do not seem to be in any way dependent on the existence or the absence of a declared cirque at the head of the glacier. If a glacier takes origin in a sharp gulch or in a pointed valley, a typical cirque

[1] Willard D. Johnson, *Jour. of Geol.*, XII, 576.

may not develop, but this does not affect the behavior of the glacier below. If a pre-existent step or down-set crosses the bottom of the valley at any point beneath a glacier, or if a step is developed by structural inequalities, and if the down-set is sufficiently great in proportion to the thickness of the ice to cause effective crevassing

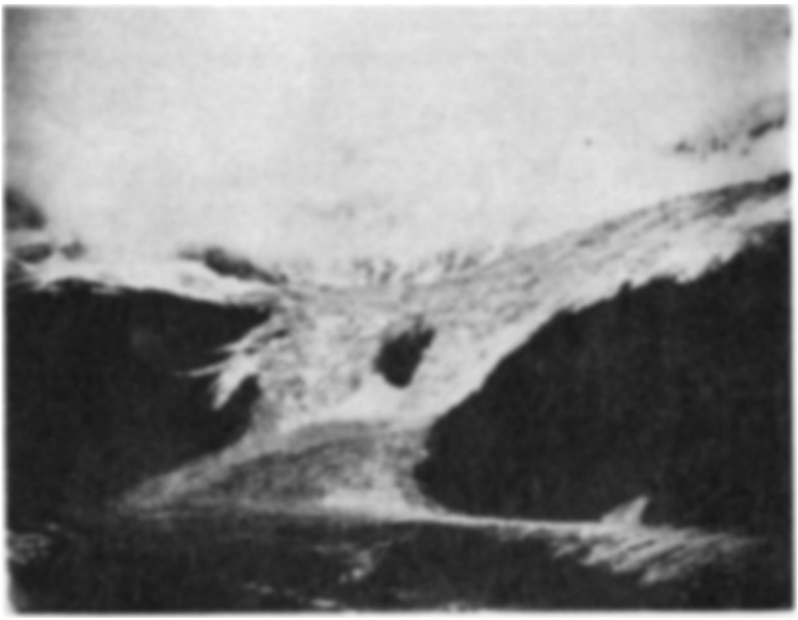

FIG. 10.—View from the Bäregg in the Bernese Oberland, Switzerland. At the bottom of the picture below the ice fall is the comparatively level Lower Eismeer of the Unter Grindelwald Glacier. Above the ice cascade is another higher ice plateau known as the Fiescherfirn, limited by the slope seen in the perspective. Peeping through the mists high above is the point of the Grosse Fiescherhorn. Photo. by R. T. C.

through the whole depth of the glacier, the conditions at the base of the step are not radically different from those at the base of the cirque wall, for there is in effect a break in the continuity of the motion of the glacier and the beginning of a new motion in the ice mass below. The rock face of the step may be regarded as a cirque wall in a modified sense. From it masses may be detached and, falling against the ice wall, become attached and dragged

forward. At the brink of the step-wall special weighting is likely to be brought to bear by the pushing of the ice forward over the brink before it breaks and drops down, and this probably leads to some splitting off of the edge of the wall. This action naturally tends to give slope to the step and to modify it in the direction of a cataract as distinguished from a cirque, but the essence of the phenomenon is probably much the same in either case. Sapping and stoping seem to be rather general phenomena of the basal action of glaciers.

FIG. 11.—The Furgg Glacier, a broad, flat, ice sheet at the east base of the Matterhorn. Both above and below this nearly level glacier-made shelf are steep cliffs. Photo. by R. T. C.

The operation of the stoping process at several points in a long glacier tongue, by developing successive ice falls between more or less level stretches, results in a rude stairway of giant tread. A portion of such a glacial stairway is shown in Fig. 10. This is the Unter Grindelwald Glacier viewed from the Bäregg. Two comparatively level stretches of glacier are visible—one above the prominent ice cascade, the other below it. They are known respectively as the Fiescherfirn and the Lower Eismeer. Dropping from the Grosse Fiescherhorn and lofty Fieschergrat to the gently

sloping Fiescherfirn are steep ice-clad slopes—the upper cirque walls. Dropping in turn from the Fiescherfirn to the Lower Eismeer is the ice cascade in the center of the picture. To the right beyond the range of this picture the level Eismeer plunges over another ice fall toward the Lütchine valley below. The last plunge, however, is perhaps more in the nature of a hanging valley at the approach to the main valley. Cataracts due to the fall of

FIG. 12.—Nearer view of the head of the level Furgg ice sheet and the Furggen Grat, whose precipitous walls are being undermined. View from the Matterhorn hut. Photo. by R. T. C.

glaciers from hanging valleys into main valleys are frequent but necessarily occur at or near the junction of the valleys. Cataracts occurring at intervals along the course of a single ice stream are presumed to be correlated with stoping action.

Fig. 11 is introduced as an example of a flat plateau-like glacier-covered tract intermediate between the mountain heights behind it and the lower valley in front. This flat plateau covers an area of approximately four square miles at a mean altitude of about 10,000 feet above the sea. Ice cascades descend toward the

lower valley from either end of it. Behind are the abrupt cliffs of the Matterhorn and the Furggen Grat (Fig. 12). The very sharp angle between the steep wall of the Furggen Grat and the Furgg Glacier which is pulling away from it affords strong evidence of the effectiveness of sapping at this critical location.

VI. BASAL SIDE EROSION

The sapping and corrasion along the side-base of a glacial valley, by which the normal V-shape is converted into the glacial U-shape, is perhaps due mainly to the better supply of carving tools furnished the sides of the glacier by infall and inwash from the slopes and cliffs on the valley sides, and by seepage from the side walls. This supposes a general similarity between the conditions at the side of the valley and those at the cirque base, except that the direction of glacial motion is different.

All these distinctive phenomena of glaciers seem to us to be expressions at once of the peculiarities of glacial erosion and of its superiority where conditions favor glacial erosion.

This view does not, however, make the superiority universal and unqualified. Obviously it does not exclude the view that snow fields while they remain in the passive state serve as protective agencies. Nor does it exclude the view that the center of a continental ice field, from which the motion is mainly radiant and limited in amount, may be protective rather than erosive when compared with normal weathering. Nor does it exclude the view that valley glaciers in some of their parts may be less erosive than normal wear and weathering would be. But these seem to us rather qualifications of the general proposition that glaciers are effective agents of erosion than contraventions of it.